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EMP MITIGATION PROGRAM APPROACH

SEPTEMBER 10, 1987

OFFICE OF THE MANAGER
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THE EMP MITIGATION PROGRAM APPROACH (U)

SEPTEMBER 1987

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FOREWORD

The National Communications System (NCS) is an organization of the Federal Government whose membership is comprised of 22 Government entities. Its mission is to assist the President, National Security Council, Office of Science and Technology Policy, and Office of Management and Budget in:

- The exercise of their wartime and non-wartime emergency functions and their planning and oversight responsibilities.
- The coordination of the planning for and provision of National Security/Emergency Preparedness communications for the Federal Government under all circumstances including crisis or emergency.

In support of this mission the NCS has initiated and manages the Electromagnetic Pulse (EMP) Mitigation Program. The major objective of this program is to significantly reduce the vulnerability of the U.S. telecommunication infrastructure to disabling damage due to nuclear weapon effects in direct support of the survivability and endurability objectives addressed by Executive Order 12472 and National Security Decision Directive 97. Nuclear weapon effects include EMP, magnetohydrodynamic EMP (MHD-EMP), and fallout radiation from atmospheric detonations. The purpose of this Technical Information Bulletin is to provide the reader with information relating to specific areas of EMP which are being investigated in support of the NCS EMP Mitigation Program.

Comments on this TIB are welcome and should be addressed to:

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ABSTRACT

The function of the EMP Mitigation Program is to assess, and where possible, lessen the potential adverse effects of electromagnetic pulse (EMP) on the nation's telecommunications infrastructure. The Office of the Manager, National Communications System (OMNCS) focuses its efforts on the Public Switched Network (PSN) because the majority of critical government users rely on the PSN to conduct their National Security Emergency Preparedness (NSEP) communication requirements.

This document presents an overall plan for the EMP Mitigation Program. To date, the OMNCS has a series of tools for quantifying EMP effects on the PSN. These tools include models for predicting the effect of EMP on network equipment and estimating the EMP stress levels that equipment are exposed to. Also available is a data base for describing the topology of a major portion of the post-divestiture PSN. Results of these activities are then synthesized into a network level model, whose function is to evaluate the performance capabilities of the EMP exposed network. In addition the network level model has the ability to perform sensitivity studies. Sensitivity studies can assess the importance of different equipment types, and they are therefore useful for identifying which equipment types most require EMP testing.

Present plans call for testing of the Northern Telecom DMS-100 and AT&T 4ESS switches, and the OMNCS is expected to receive an update of network data information in 1988. However, the OMNCS needs additional data on PSN networks as well as equipment EMP test data. Such information is required in order to have greater confidence in the results of network level analyses. As confidence increases, the utility of applying network level results in planning OMNCS initiatives will be increased. In addition, continued study and research of the PSN is needed, as the PSN is a complex and continually changing system, especially following the 1984 divestiture.

Future efforts will entail analyzing the effects of traffic on the performance of EMP degraded networks. A combination of continued modeling efforts as well as applying traffic engineering theory, such as the Erlang B equation, will be used to assess how the network responds to NSEP user traffic. Activities under this field are under the heading, "Network Dynamic Stability."

All of the described efforts have been associated with identifying how the network responds to EMP. However, very little energy has been applied to mitigating, which is the long term goal of the program, EMP effects. The OMNCS believes that it is first necessary to understand what is occurring in the network <u>before</u> supporting mitigation implementations. This type

of planning ensures that funds are not wastefully spent on initiatives that will bear little or no gain to the survivability of the PSN. Once sufficient knowledge is known on EMP effects, effective efforts to mitigate EMP can be identified and implemented.

In summary, the plan of the EMP Mitigation Program is to continue sponsoring EMP test programs of critical network components, obtain network topology information, and develop additional modeling capabilities. Concurrent efforts will study PSN structure, operations and future trends, such as signaling system seven (SS7). Future efforts will address the effects of traffic on EMP exposed networks. The results of these activities can then be used to develop and implement effective mitigation strategies. Following this approach will ensure that the OMNCS attains maximum quantitative benefits of their available resources.

TABLE OF CONTENTS

LIST OF EXHIBITS

LIST OF EXHIBITS (CONTINUED)

1.0 INTRODUCTION

This document sets the framework for future efforts within the Electromagnetic Pulse (EMP) Mitigation Program with respect to analyzing, and attempting to lessen, the effects of EMP on the Nation's telecommunications infrastructure. Both National Security Decision Directive (NSDD) 97 and Executive Order (E.O.) 12472 call for the ability to maintain communication capabilities in times of national disaster, which includes a nuclear attack. Electromagnetic pulse is a byproduct of a nuclear detonation, that is characterized by intense, high-frequency electromagnetic fields. The currents induced on telecommunications equipment may be sufficiently severe to damage the telecommunications resources used by critical government users. Hence, the need for the Office of the Manager, National Communications System (OMNCS) to sponsor the EMP Mitigation Program is established.

1.1 PURPOSE

The EMP Mitigation Program was established to analyze, and where feasible lessen, the degradation effects of EMP on national telecommunication resources. The program focuses its efforts on the resources of the Public Switched Network (PSN) because the majority of NCS member organizations rely on the PSN for conducting their National Security Emergency Preparedness (NSEP) communication responsibilities. The primary NSEP responsibility is currently for voice capabilities. This requirement is reflected in the scope of the EMP Mitigation program.

The PSN is a vast, complex, commercial resource. It encompasses the entire nation with sophisticated equipment, and and is continually changing with the implementation of newer technologies, especially since the divestiture of AT&T in 1984.

Because the PSN is comprised of private companies, the OMNCS has little direct control over how it operates and the equipment it employs. These issues are dictated by the commercial marketplace. In addition, the firms are often competing with one another and are apprehensive of providing, due to proprietary reasons, information on their structure and operations. This information is necessary, however in assessing network survivability against EMP. Such conditions make it very difficult to assess the effects of EMP on the PSN. However, it is the belief of the OMNCS that PSN EMP effects can be estimated to an acceptable degree. These estimates will be useful for developing long-range EMP initiatives.

In the OMNCS' effort to enhance the EMP survivability of the PSN, it is first necessary to understand how EMP affects the network. This is the stage at which the OMNCS currently resides. A series of modeling tools, data base processing and equipment EMP testing programs have been developed and supported for such a purpose. As these efforts continue and mature, a more accurate understanding of the network level EMP effects is attained. Such network level analyses results can then be used to identify, and where economically possible, implement EMP Mitigation strategies within the PSN.

This report integrates all the efforts within the EMP Mitigation Program and provides a mutual focal point for assessing and enhancing the survivability of the PSN to EMP. A plan is presented and discussed that indicates how equipment EMP test data, network modeling tools, and EMP mitigation strategies are merged in pursuit of this common goal. This plan is useful for identifying future efforts within the EMP Mitigation Program and for ensuring that such efforts are consistent with the long-range objectives of the program.

1.2 BACKGROUND

The EMP Mitigation Program uses an evolutionary process for continually improving the understanding of EMP effects on the PSN. The basis for the analyses is the survivability of individual switches and transmission facilities. This information is then integrated with the topology of the network and the EMP threat, to estimate post-attack connectivity. The key phrase is "network level," because the OMNCS' concerns are with the communication capabilities of government users. These capabilities cannot be determined by only analyzing the individual network equipment; the entire network must be assessed.

Previous efforts under this program have focused on the expected post-attack connectivity of Public Switched Network (PSN) switches. The first analyses were based on the physical connectivity of network switches (i.e., which switches have a path via transmission facilities to other switches). Physical connectivity provides the foundation for understanding the overall availability that the network can provide to government users. Subsequent, more advanced analyses focussed on the logical connectivity of the EMP exposed PSN. The logical connectivity implies the existence of physical connectivity as well as the ability of the network to use the physical assets to develop a connection.

These analyses have not taken into account the telecommunications traffic that will be supplied to the PSN in a post-attack environment. This will be the subject of future efforts, referred to as "Network Dynamic Stability." First a methodology will be developed, followed by network level analyses. Efforts within network dynamic stability will focus on traffic theory to characterize call processing within network switches and transmission facilities. The result of these efforts will indicate the availability of the network to an NSEP user. To assess availability the models must assess physical connectivity, logical connectivity and network traffic.

In support of these network level analyses the OMNCS has developed a set of mathematical and computer modeling tools. These tools all interact with one another for a common end result--to predict the connectivity of the PSN following EMP exposure. In addition these tools are also valuable to the OMNCS for supporting EMP testing efforts through sensitivity studies. This is done by quantitatively specifying the equipment types which are most critical to the overall performance of the network. Those equipment types identified as being most important are given the highest testing priority because it is necessary to understand the performance of critical equipment types in order to accurately assess the performance of the entire network. Recent analyses have indicated that the AT&T 4ESS switch and a solid-state transmission facility, such as the AT&T DR11-40 system, should be EMP tested.

In addition to assessing EMP effects, the OMNCS has expanded efforts to analyze fallout radiation. Like EMP, fallout radiation is a byproduct of a nuclear detonation. It is the residual radiation left following a blast, which can be carried by weather conditions, such as wind and rain, to locations far from the destination point. Fallout radiation is also a potential threat to the survivability of network resources, though its effects take longer to manifest than EMP. The OMNCS' efforts within the fallout radiation area are not nearly as mature as the efforts within EMP. To keep this report focused, only the EMP activities will be addressed.

1.3 NETWORK LEVEL APPROACH

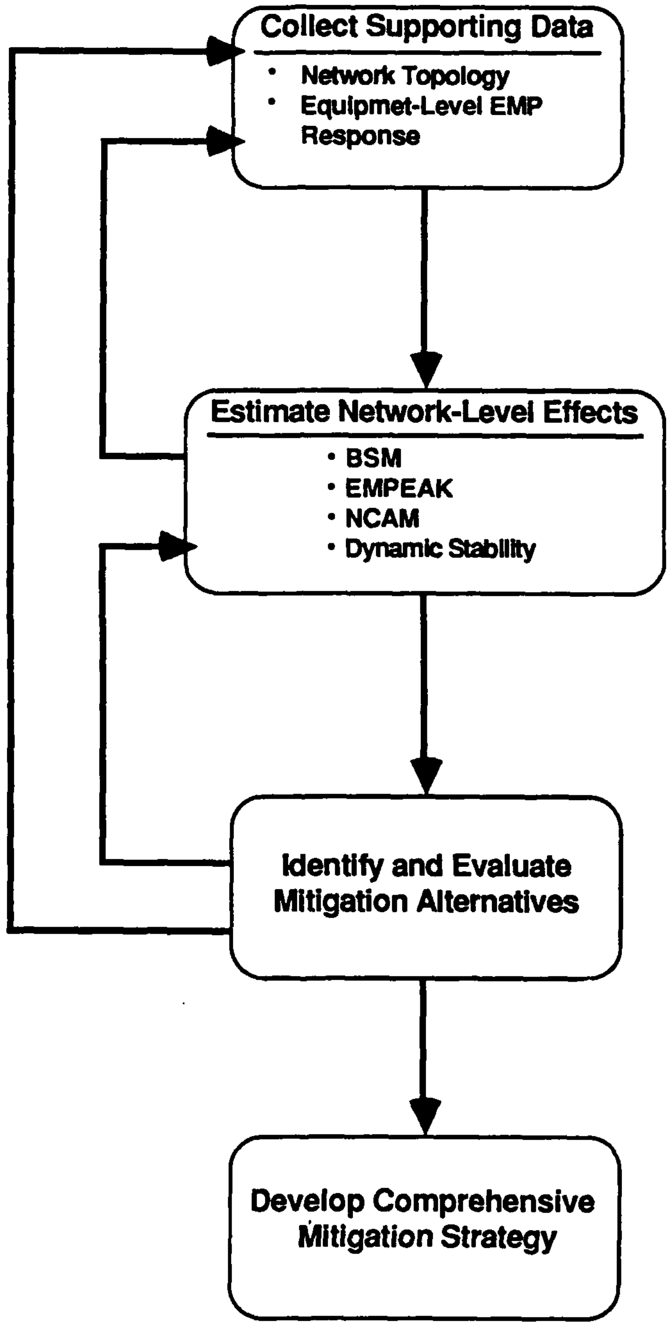
The methodology for analyzing EMP effects can be conceptualized by describing the flow diagram of Exhibit 1-1. The top box specifies the data that is required to support network level analyses. The OMNCS currently has a data base describing the AT&T toll portion of the PSN, and is continuously working on obtaining the topologies of other networks, as well as local exchange information. Presently, the OMNCS has data on a representative, though not comprehensive, portion of equipment types employed in the PSN. The feedback arrow indicates that this is an evolving process. For the OMNCS needs more thorough data than it now has to more accurately describe and mitigate network EMP effects. In addition, the network is continually changing and obtaining the data that reflects the changes data is necessary.

To effectively use the supporting data a set of models have been, or are in the process of being, developed by the OMNCS as tools for quantifying network level EMP effects. The Bayesian Survivability Model (BSM) assesses equipment survivability based on EMP test data. Specification of the EMP stress levels at network equipment locations is performed by EMPEAK. The Network Connectivity Analysis Model (NCAM) is a simulation tool that characterizes the capabilities of an EMP stressed network. Present efforts are working with the Network Dynamic Stability Analysis, which can predict the availability of the post-attack network to NSEP users. This model must take into account the effects of physical and logical connectivity, as well as the traffic that is injected into the network. The model shall quantify availability by call blocking probability and expected end-user time delays.

Analyses results obtained from the models provide valuable data for identifying, evaluating and comparing EMP mitigation

EXHIBIT 1-1

The Evolutionary OMNCS Approach
to Assessing Network Level EMP Effects



strategies. A hypothetical example application could be the derived connectivity benefit obtained from EMP hardening PSN 4ESS switches. Again, the feedback arrow indicates continued analysis due to the constant changes in the PSN. Based on all these efforts, the OMNCS will have developed a comprehensive EMP mitigation strategy.

As indicated in Exhibit 1-1, the EMP Mitigation Program uses a series of parallel efforts. Present capabilities can produce first-cut estimates of network performance, and continued efforts are needed to more accurately predict network performance. However, many of the tools which accurately predict survivability have already been developed. As the OMNCS obtains more information, primarily in the areas of equipment testing and network topology, the understanding of network level effects will be improved.

1.4 ORGANIZATION

The models that are currently employed to estimate network level EMP effects are discussed in Section 2.0. This includes an in-depth presentation of the Bayesian Survivability Model (BSM) to quantify equipment performance, the EMPEAK model, data base processing for describing the network topology, and the NCAM model. These tools have been successfully employed in previous efforts, and they will serve as a foundation for future efforts.

Section 3.0 presents issues that will be analyzed in future efforts. These issues primarily focus on how traffic will be handled by an EMP exposed network. The analyses will use detailed traffic engineering principles to describe the call blocking probability in switches and transmission facilities, and then synthesize the information to predict network level call blocking. Activities in this area fall under "Network Dynamic Stability Analysis."

Section 4.0 addresses current testing activities that are part of the program. This includes past testing activities as well as future efforts. Of special interest is the partial degradation of switches, where the switch retains only a portion of its original call processing capabilities.

The utility of this approach to the OMNCS is the subject of section 5.0. This section addresses how alternative EMP Mitigation strategies may improve network performance and how the computer modeling tools may support EMP testing efforts. Also described are sensitivity studies which can identify which equipment types most require testing.

Recommendations for future efforts within the EMP Mitigation program are supplied in section 6.0. Projected activities include additional equipment EMP testing, computer modeling development, PSN data base processing and a study of PSN operations and future trends.

2.0 NETWORK PERFORMANCE MODELING CAPABILITIES

To characterize the survivability of the national telecommunications infrastructure, the OMNCS has developed a balanced approach consisting of EMP stress tests on critical telecommunications network elements and the use of equipment performance data in network simulation models to predict user connectivity levels. This section describes existing computer-based models used in the EMP Mitigation Program to measure network performance. First, the available data resources on the PSN topology are presented. Last, the previously developed models, BSM, EMPEAK, and NCAM are discussed.

2.1 DATA RESOURCES AND NETWORK TOPOLOGY

The EMP Mitigation Program can handle information for any telecommunications network. The network addressed in the EMP effects analyses is the toll portion of the post-divestiture AT&T network. This network contains complete information on the AT&T network transmission and switching facilities as of January 1986 and represents an accurate and current description of a major portion of the PSN. This data base, obtained by the OMNCS as part of its Nationwide Emergency Telecommunications Service (NETS) Task 3 initiative, is the most comprehensive one available to date, and has been extensively studied and processed to support detailed analyses. The function of NETS is to provide enhanced routing services not normally supported by the PSN to critical government users in emergency conditions. The enhanced routing is attained by providing network elements with additional intelligence, not part of the present PSN, that allows the network to "piece together" surviving physical resources for end-to-end logical connectivity. The OMNCS is expected to receive updates to the existing data base, including new switch and span locations as well as homing arrangements, in April 1988.

2.1.1 Network Topology Specification

Along with data on the post-divestiture toll portion of the AT&T network, a limited amount of available local level topology information is also integrated into the relational data base. The information exemplifies the topology information required for further data collection from other carriers. The data base has been formatted and processed to produce the following information:

- Switch locations
- Switch types
- Switch interconnections
- Transmission facility locations
- Transmission facility types.

Understanding the network with this degree of fidelity supports detailed EMP effects analyses.

The network analyzed in this approach is composed of 344 switches, where each switch performs one of the following tasks:

- End-office - The switches to which end-users are connected.

- Access Tandem - Connects end-office switches and routes their traffic to the proper long-distance carrier Point of Presence (POP), which in this case is an AT&T POP.

- POP - These switches are the entrance to the toll network. POPs are connected to toll switches and other POPs in the toll network.

- Toll - Routes traffic within the toll network. Toll switches are connected to POPs and other toll switches.

An illustration of the interrelationship of these switch classes is presented in Exhibit 2-1. A list of the AT&T switch types, the location of each switch and the quantity of each switch is included in Exhibit 2-2. Note that the AT&T network sometimes employs switches manufactured by other companies.

EXHIBIT 2-1
Relationship of Network Switches

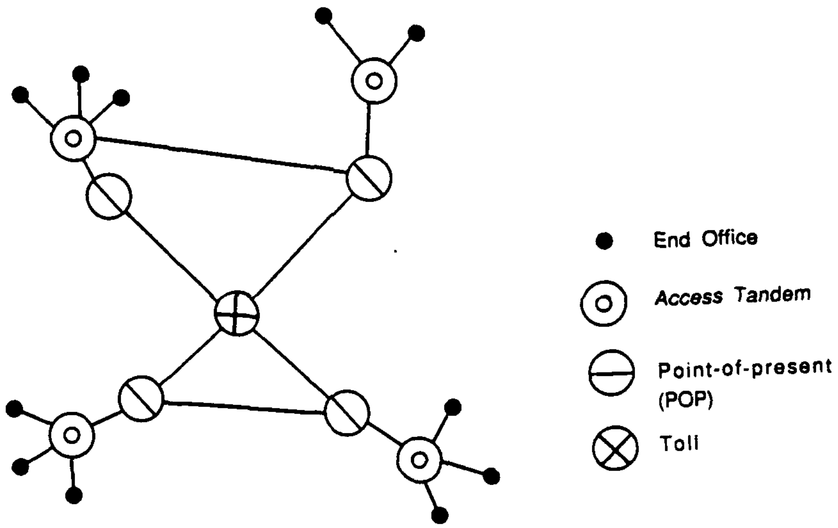


EXHIBIT 2-2
Switch Types and Quantities

Switch Type	Manufacturer	Quantity
1ESS	AT&T Technologies	31
4ESS	AT&T Technologies	104
5ESS	AT&T Technologies	29
DMS-200	Northern Telecom	19
DMS-100/200	Northern Telecom	1
EAX3	Automatic Electric (GTE)	3
EAX5	Automatic Electric (GTE)	3
DCO200	Stromberg Carlson	1
Unknown Toll		20
Unknown End Office		133

Exhibit 2-3, also generated from the data base, summarizes the transmission facility types and the corresponding percentages of these facilities which exist in the network.

EXHIBIT 2-3

Transmission Facility Types and Percentages

Transmission Facility Types	Percentage (%) of network
Digital T Carrier	18.9%
Analog L Carrier	12.0%
Analog Microwave	59.0%
Digital Microwave	5.6%
Analog N Carrier	1.6%
Fiber Optic	2.7%
Satellite	0.2%

2.1.2 Assessment of Equipment Survivability

The OMNCS has conducted EMP tests, or has obtained test data from other government agencies, on the following set of PSN telecommunications equipment types.

- AT&T Technologies 1ESS switch
- AT&T Technologies 5ESS switch
- T1 carrier transmission facility
- TD-2 microwave transmission facility
- L4 carrier transmission facility
- FT3C multimode fiber optic transmission facility
- D4 channel bank.

This set of equipment represents a significant portion of the equipment types employed in the PSN. First-cut network level analyses have been conducted using this equipment set as the foundation for assessing the survivability of all

PSN equipment. A summary of the equipment EMP effects for the seven tested equipment types is available in reference 1. A more detailed explanation of the EMP Mitigation Program testing efforts is provided in section 4.0.

The criteria by which survivability is quantified is the EMP field strength. Factors such as building construction, the specific model of the equipment type and building polarization with the weapon are not accounted for as such additional factors would make survivability assessments intractable. Making assessments through a single factor is referred to as the "collective risk" approach. Using this approach is generally not acceptable for a single equipment, but is acceptable for a large sample size, such as all the equipment of the PSN.

2.2 NETWORK LEVEL MODELING APPROACH

The EMP Mitigation Program uses a network level approach to assess EMP effects on network performance. The network level approach is composed of the following four modules:

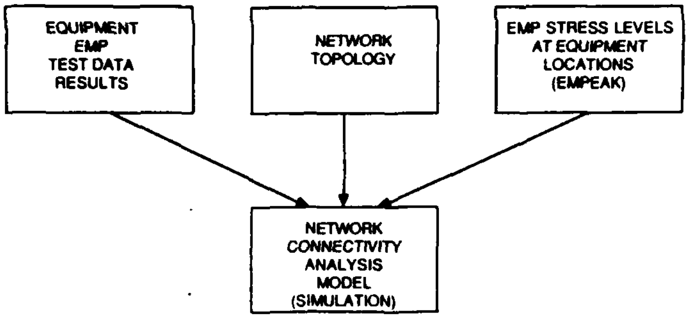
- Network topology specification
- Assessment of equipment survivability
- Prediction of EMP field strengths
- Modeling network performance.

The interrelationship of these modules is presented in Exhibit 2-4. The network topology specification is achieved by processing the AT&T toll network data base. Equipment survivability is assessed with the BSM, which uses EMP test data to characterize the response of EMP exposed telecommunications equipment. The EMPEAK computer model specifies the EMP field strengths that network equipment locations are expected to receive. The NCAM

EXHIBIT 2-4

Network Level EMP Effects Approach:

Functional Flow Diagram



model integrates network topology information, along with the EMPEAK and BSM outputs, to calculate network performance using a Monte Carlo process. At the conclusion of the Monte Carlo process two primary statistics are calculated, the mean and the standard deviation of the point-pair connectivity replications. Point-pair connectivity is a measure of the surviving connections with respect to the original connections, and is useful in assessing the post-attack telecommunications capabilities of a network. Both physical and logical connectivity are calculated by NCAM using the point-pair metric.

2.2.1 Bayesian Equipment Survivability Model (BSM)

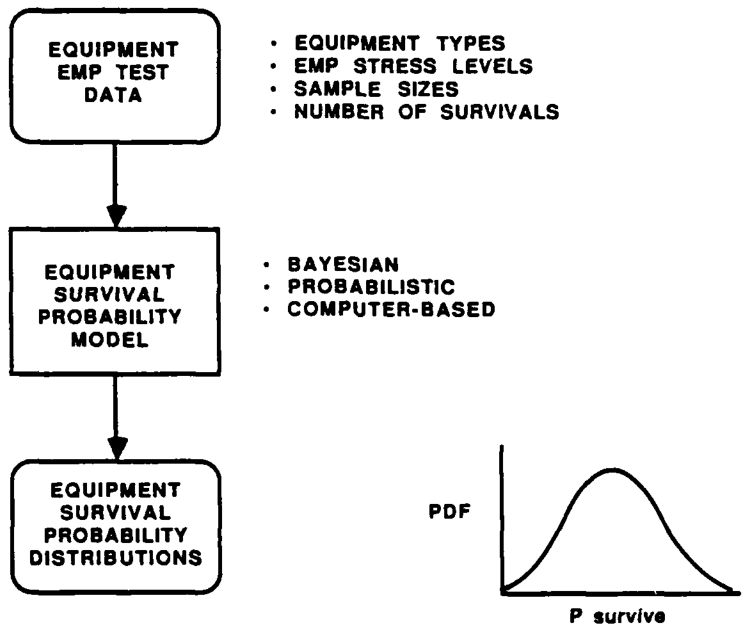
Predicated on Bayesian statistical theory the BSM is designed to characterize the EMP-induced survival probabilities for different types of telecommunications equipment (network elements). The full mathematical explanation of this approach is available in reference 2. Exhibit 2-5 illustrates the flow of the BSM.

The computer-based model assumes that before EMP testing, no knowledge on equipment survivability is available. This assumption is mathematically characterized by the

EXHIBIT 2-5

Bayesian Survivability Model:

Functional Flow Diagram



noninformative prior distribution. The EMP test data results, which specify the number of EMP exposures and the number of survivals, are fed into the BSM model to modify the noninformative prior distribution. A numerical approximation of the Cumulative Distribution Function (CDF) of survival probability is calculated from the beta posterior distribution. Numerical approximations are used to characterize CDF curves describing the probability of equipment survivability. The beta posterior distribution is obtained by performing a Bayesian process on the assumed noninformative prior distribution and the equipment EMP test data.

For each tested equipment, a unique CDF curve is developed for the EMP stress level ranges: low (10-30 kv/m), medium (30-50 kv/m), and high (50-70 kv/m). This classification is necessary because not all equipment have been tested at the same discrete EMP stress levels. This approach is suggested and supported in reference 3. The results of the BSM are subsequently used as inputs to NCAM.

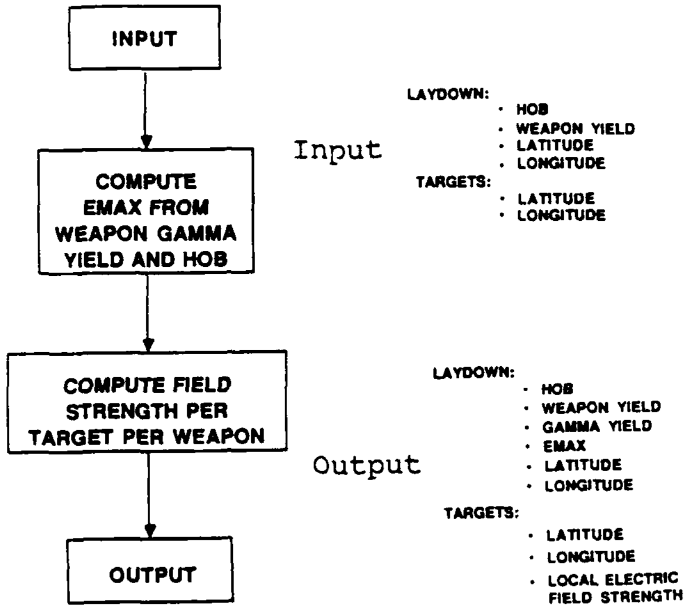
2.2.2 EMP Field Strength Model (EMPEAK)

The computer-based model, EMPEAK, is used to obtain estimates for the electric field strength at each switch and transmission facility location under study after an exospheric nuclear explosion over the Continental United States (CONUS). Herein, the term telecommunication facilities will refer to both switches and transmission facilities.

2.2.2.1 EMPEAK Procedure. EMPEAK is based on the exospheric burst threat that causes widespread effects on telecommunication facilities. The magnitude of the electric fields generated by a high-altitude explosion depend on the height and yield of the burst, the gamma yield of the weapon, and the position of the target with respect to the burst and the local magnetic field of the earth. For any weapon laydown scenario available to the OMNCS, the model has three tasks to perform (Reference 4). First, it must estimate the gamma yield from the weapon yield. If the gamma yield is provided, the model disregards this calculation and uses the available gamma yield. The second function of the model is to determine the maximum electric field strength from both the weapon gamma yield and height-of-burst (HOB). Third, based on the maximum electric field, the model calculates the local field strength for every potential target within CONUS. This third value is determined by using the HOB and a digitized map of EMP surface variations to obtain the EMP ground coverage for the burst. The functional flow of this approach is shown in Exhibit 2-6.

EXHIBIT 2-6

Functional Flow Diagram



2.2.2.2 EMPEAK Model Inputs/Outputs. The data required as input to the model comprise two categories: scenario and targets. The latitudinal and longitudinal coordinates of the burst as well as the HOB and weapon yield describe each scenario. Within each scenario, several bursts typically occur. The spatial coverage of high-altitude EMP over the surface of the earth is determined by the height of weapon burst. Targets define the telecommunication facilities under study and are identified solely by their latitudinal and longitudinal coordinates within CONUS.

For each exospheric explosion, EMPEAK estimates the field strength at every target. After all the bursts have been examined, the largest value at each target is the determined output. Based on this information, EMPEAK has the capability of performing a first order approximation of the EMP field strength at any CONUS location. The results obtained from this model are used as inputs for NCAM to assess the EMP effects on network performance.

2.2.3 <u>Network Connectivity Analysis Model (NCAM)</u>

The Network Connectivity Analysis Model (NCAM), a discrete event simulation, assesses network performance by using all of the previously discussed information, such as, network topology, equipment survivability, and expected EMP stress levels, as input data. Exhibit 2-7 provides the NCAM functional flow diagram. By understanding the network structure and the expected EMP stress levels, the stress level to which each set of equipment is exposed is obtained. Next, the survivability of <u>each</u> equipment set in the network is determined using the BSM. Processing this information and performing multiple Monte Carlo simulations yields the point-pair connectivity network performance metric. This connectivity metric is a quantifiable measure of the telecommunications capabilities of an EMP-exposed network.

An example of the Monte Carlo procedure is provided in Exhibit 2-8. As shown, multiple tests are performed on the network. Each network element is assigned a random survivability value selected for the particular EMP stress level under study. This value is compared to another survivability value sampled from the tested element's CDF curve The element survives if the sampled value is larger than the assigned value. Each element's survivability for one simulation is independent of its survivability for another simulation, meaning different equipment may fail in different simulations. Following the completion of all the network simulations the mean (average) and standard deviation of the connectivity metrics for the entire Monte Carlo process are calculated. The standard deviation provides insight into the likely distribution of connectivity measures among the different simulations.

EXHIBIT 2-7

Network Connectivity Analysis Model:
Functional Flow Diagram

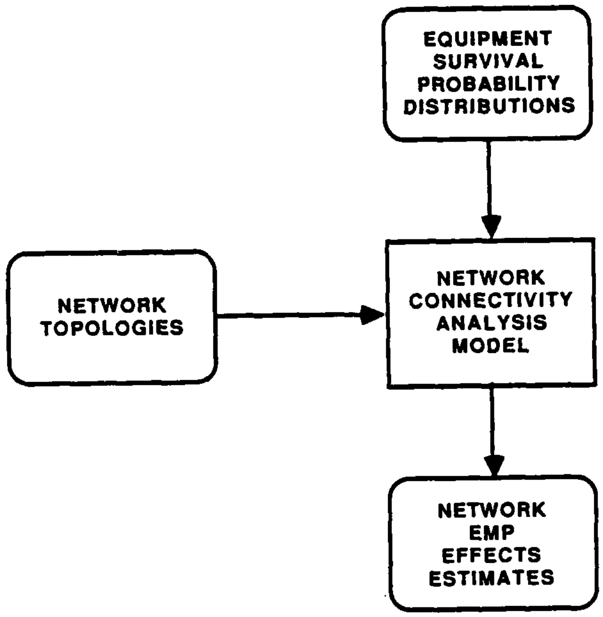
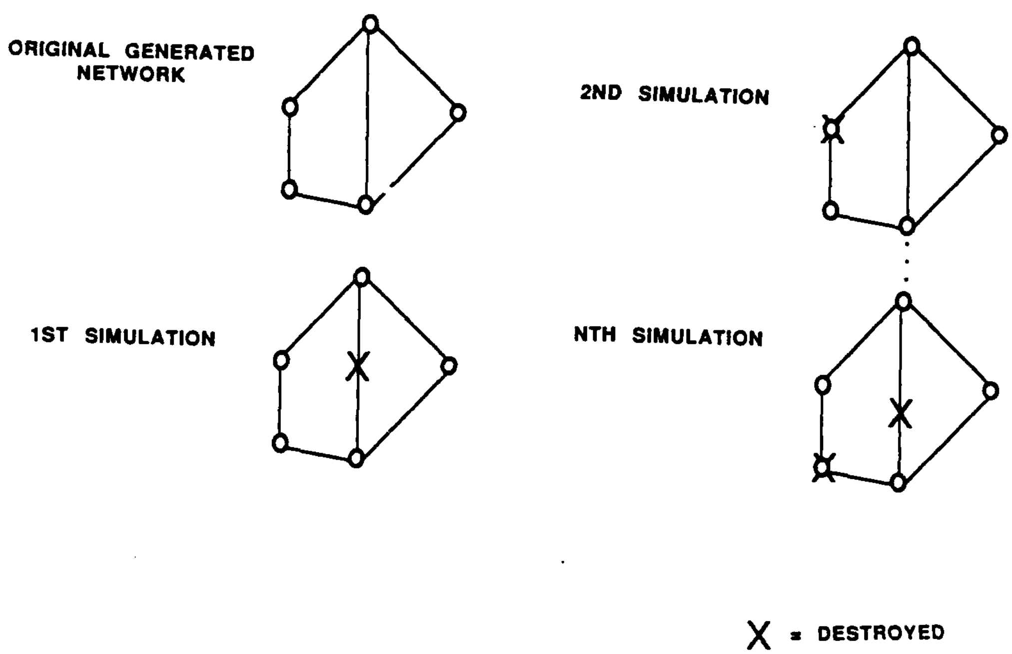


EXHIBIT 2-8

Monte Carlo Procedure



The measure used to quantify network performance based on the surviving network equipment is the physical and logical point-pair connectivity metrics. Physical connectivity represents the upper bound in communication capabilities. Two switches are physically connected as long as there is either a direct connection, or an indirect connection traversing through intermediate switches, between them. Logical connectivity requires a physical connection <u>and</u> the network capability to support communications over the physical connection.

Point-pair connectivity, which is the metric chosen to quantify network performance, is a function of the original connections versus post-attack connections. The metric is defined by the ratio given in equation 2-1.

$$\text{(2-1)} \quad \text{point-pair connectivity} = \frac{\text{\# of surviving connections}}{\text{\# of original connections}}$$

NCAM has the capability of calculating two logical connectivity metrics: baseline and NETS. Baseline connectivity represents the capabilities of the PSN network in its present form. NETS connectivity shows network communications with an enhanced routing mechanism.

In the pre-attack network each of the switches are logically connected to every other switch. Two switches are logically connected in the PSN baseline as long as they take three Originating Route Identification Numbers (ORINs) or less to reach each other. ORINs are the set of physical transmission facilities that comprise a connection between switches. In many cases, an ORIN directly connects two switches; and in other cases ORINs must be concatenated together to logically connect two switches. NCAM simulates the routing flexibility provided by NETS. That is, NCAM models NETS by allowing up to twelve ORINs between each pair of switches for a logical connection.

2.3 SUMMARY

As presented above, the models developed under the network level approach for assessing the effects of EMP on PSN resources support quantitative estimations of service degradation that NSEP telecommunications users can expect to experience as a result of EMP. The models reflect a balanced OMNCS program of testing and analysis aimed at identifying and, if possible, mitigating EMP effects on NSEP telecommunications capabilities. The results of these models can address the benefits of NETS and other PSN-based OMNCS programs in countering EMP effects. In addition, the models have the capability of supporting sensitivity studies which indicate the testing priority that should be placed on particular PSN equipment types. Through the continued evolution of the network level approach, improved understanding of network structure, and additional EMP test data, the OMNCS will continue to estimate the EMP effects with increasing accuracy leading to greater confidence in the network level results.

3.0 NETWORK DYNAMIC STABILITY ANALYSIS

Tests and analyses of telecommunications switching and transmission systems indicate that EMP effects might not make the equipment fully inoperable, but rather reduce its call processing capabilities. The reduced equipment capabilities could render certain end-to-end connections impossible, induce call blocking, and introduce time delays in network responsiveness to operational user requirements. The EMP Mitigation Program plans to include network stability analyses in the investigation of EMP effects on network performance. These analyses are an extension of the previous modeling efforts described in section 2.0. The primary aim of the Network Dynamic Stability Analysis effort is to develop a methodology for assessing the effects of reduced equipment call prcessing capability and time response of EMP exposed equipment on network performance.

This section introduces network overload and its impact on call completion probability and user service time delays. A useful telecommunications construct termed availability will also be presented. This section is concluded with a discussion of the method and results of an initial network stability study.

3.1 PROBLEM OVERVIEW

A significant concern for NSEP telecommunication users and network designers is the problem of overload. Network overload occurs when switches and transmission facilities receive more traffic than they can accommodate. Ultimately, an overloaded network has less call processing capabilities than an unstressed network, i.e. one receiving less traffic than the maximum designed level.

3.1.1 Problem Definition

Under normal operating conditions, where each call request requires an end-to-end connection, a sequence of intermediate transmission and switching facilities is needed to set up the circuit. This sequence is disrupted as direct routes in a network become occupied; more calls are forced to take alternate routes, which involves more trunks and switching systems per call. Hereinafter, the terms bandwidth, servers, circuits, and trunks will be used interchangeably to describe the transmission facility capacity. That capacity is just the maximum number of simultaneous independent paths over which traffic flows. As resources become over-burdened with traffic, the availability of circuits may be reduced to unacceptable levels. Moreover, the resultant impact on the network call processing capability could be severe. Typically, four events contribute to the disruption of the call completion sequence and thereby induce traffic overload in a network.

- The accumulation of calls not completely processed and which, by the virtue of their presence in the network, continually take up a percentage of the resources

- A reduction in the outgoing carried traffic that produces an increase in the call attempts (or retries) originating in the network

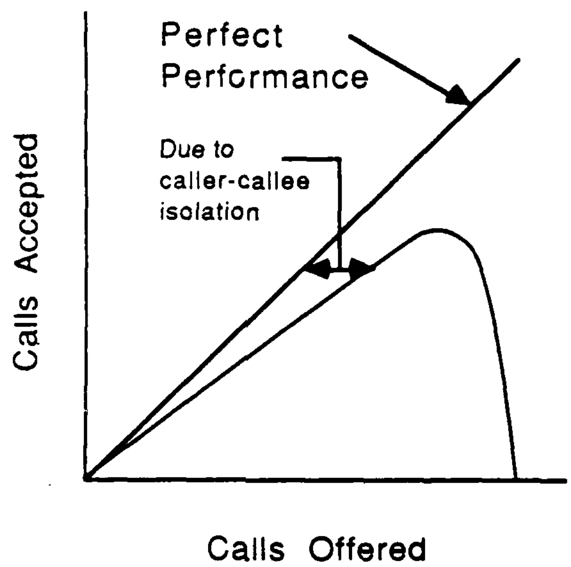
- A logical disconnection between two end-users due to EMP

- A reduction in network equipment capabilities due to EMP.

As a result of these events, the efficiency of the network decreases. If no preemptive measures are taken, the end-user's unsatisfied demands are likely to be repeated and further congest the system whose response curve takes the form illustrated in Exhibit 3-1.

EXHIBIT 3-1

Carried Load Versus Offered Load



As shown in Exhibit 3-1, carried traffic typically decreases when the offered traffic exceeds some threshold of normal operation because partially completed requests tie up network resources while trying to acquire other resources tied up by other uncompleted requests. Users whose attempts are blocked frequently hang up and try again, thus increasing the offered load even more. For emergency communication analyses, retries are expected to produce a significant portion, if not a majority, of calls offered to the network. When extremely heavy traffic exists, many network resources are held by partially completed requests and few complete connections can be established. Solutions to ensure efficient use of common resources of a heavily loaded network require some form of network management.

Also illustrated in Exhibit 3-1 and listed above are two events that may occur within an EMP damaged network: first, end-points may be isolated from one another; and second, existing facilities may exhibit a reduced processing capacity. The first situation points out that even at low offered load rates many calls may not be handled due to this break in logical connectivity. Moreover, an end-user, unaware that there is a logical disconnect, would likely retry the call; these retrys have the effect of further increasing the offered load.

As a result of the second situation, a potentially degraded end office, access tandem, or PBX may be unable to service the offered traffic from users and transmit that traffic to the interexchange networks. The degraded switching system's ability is affected by the amount and nature of offered traffic, telephony operating procedures for handling incoming traffic from interexchange carriers during congested periods, and the reduced available channel capacity due to EMP. Reduced processing capacity may further limit toll network level call handling activities.

3.1.2 Overload Analysis

Various network control utilities have been developed to mitigate the network level effects of over-stressed call processing. These include queuing incoming calls in a Last In First Out (LIFO) sequence; blocking outgoing calls; and removing non-critical parts of the call routing process, such as, monitoring equipment. A discussion of these utilities is beyond the scpope of this report, though such a discussion can be found in reference 6. The OMNCS is contributing to this effort by developing simulations to identify network vulnerabilities and countermeasures to ensure network stability. Basic to these simulations is the mathematical construct called "blocking probability." Call blocking probability pertains to the percentage of call attempts that cannot get through to the destination, i.e. they encounter an all servers busy condition. By understanding the blocking probabilities for the individual switches and trunks, overall network blocking probabilities can be developed between each pair of switches using graph theory techniques. Such techniques combined with network simulation will accomplish two tasks:

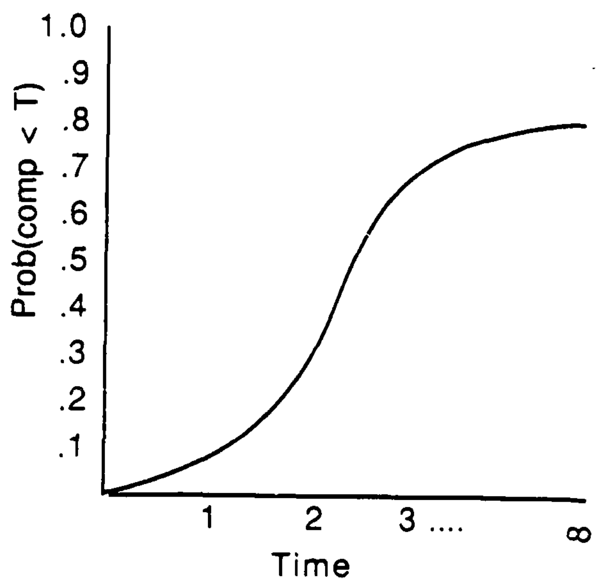
- Simulate reduced switching capacity due to EMP
- Calculate the percent of offered load successfully routed to destination switches by simulating actual traffic flow.

The resulting measure of call completion performance would be the probability that a call attempt from an NSEP telecommunications user is blocked at any discrete time due to network EMP degradation.

As one of the objectives of the Network Dynamic Stability Analysis is to estimate time delays, the instantaneous call blocking probabilities may be used to calculate the probability distribution of the time delays experienced by users. Time delay is defined as the time between a user's call initiation (dialing the phone number) until the destination's phone rings. Initial efforts will focus on the development of various mathematical and algorithmic techniques to analyze network time delay effects that may take the form of Exhibit 3-2. The time delay probability distribution, shown below, characterizes the probability that a user waits less than a given period of time before having the call successfully completed. The waiting time may be due to network delays in establishing the end-to-end connection, or the caller needing to make multiple attempts when previous attempts have been blocked. Note that in some cases the call never gets through, which indicates that the users are logically disconnected.

EXHIBIT 3-2

Delay Probability Distribution



The goal of the Network Dynamic Stability Analysis is to measure the ability of interexchange networks to carry offered traffic from originating switches to terminating switches under conditions of EMP degradation. In support of this effort the Network Dynamic Stability Analysis will simulate the ability of the interexchange (toll) portions of the PSN and NETS to successfully route the traffic offered by the serving switches. The results of this analysis, in the form of call completion probability and user service time delays, will enable the OMNCS to better quantify the impact of network congestion and evaluate network management techniques.

3.2 AVAILABILITY

The OMNCS evaluates the network performance through a system of comprehensive measurements: connectivity, call blocking probability, and user service time delays. In compliance with present objectives, these measurements are used to identify network performance levels. The overall process of measuring, assessing and reporting both the quality of service provided to users and the efficiency of the network and its associated operations yields the network "availability." Availability measures the continuity of signaling service between users and the degree to which network facilities are accessible to support the traffic demands of the users. User service time delays and call blocking are examples of availability measurements.

To properly model network performance, the OMNCS will first investigate appreciable decreases in channel and switch availability due to reduced call processing capabilities by applying classical telecommunications traffic theory. Second, the OMNCS will characterize network behavior to overload in an EMP stressed environment by developing network simulation models and analytical tools and by modeling the technical operations of the PSN. Third, the OMNCS will calculate time delay probability distributions to further determine the average call time delay (distribution mean) and the percent of users experiencing time delays exceeding certain values (distribution percentiles). Finally, the OMNCS will ensure that the refined analysis concept of predicting call blocking and delay distribution can be implemented for the PSN and NETS given the potential restrictions on the available supporting data. The data restrictions are primarily with regard to obtaining the network topology information of the nation's primary commercial carriers. Comprehensive results of telecommunications equipment and network analyses will be presented in upcoming Network Dynamic Stability Analysis work.

3.2.1 Transmission Facility Availability

A common way of predicting transmission facility availability is through the Erlang B equation (Reference 5):

$$B = \frac{(\lambda \cdot t_m)^N}{N! \sum_{i=0}^{N} \left(\frac{(\lambda \cdot t_m)^i}{i!} \right)} \tag{3-1}$$

B = call blocking probability

λ = call arrival rate (calls/unit time)

t_m = average call holding time

N = number of servers (trunks)

The call arrival rate, λ, solely addresses original calls and neglects retries. However, λ_{eff} includes retries by incorporating an infinite series into the following calculations:

$$\lambda_{eff} = \frac{\lambda}{(1 - B)} \tag{3-2}$$

The results of equations 3-1 and 3-2 are obtained and used iteratively to determine asymptotically stable values for B and λ_{eff}.

Based on these two equations the blocking probability of a transmission facility between two switches can be calculated. The calculation requires information on the trunk bandwidth and the end-user demand, typically quantified by call arrival rates and call holding times. This method of determining trunk blocking, common within the telecommunications community, is useful for analysis of transmission facility behavior under overload.

3.2.2 Switch Availability

As retries due to trunk blocking combine with the heavy overload of initial call attempts, the switching system also becomes congested. Typically, blocking within switches may occur for two reasons:

- Offered load is too great for a properly functioning switch to process.

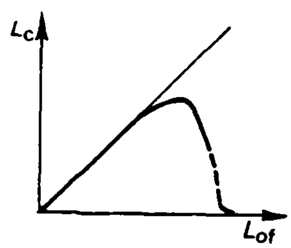
- Switch is operating at reduced capacity, perhaps due to EMP disturbance. Therefore, the switch cannot process its full traffic load.

Exhibit 3-3 illustrates the switch blocking that results from the situations described above.

Switches are designed to support a certain amount of call processing, such as a carried load of 70,000 calls per unit time. In the linear region of Exhibit 3-3, the switch operates in a stable mode; the switch processes each call it receives; that is, the load carried (L_c) is equal to the load offered (L_{of}). Once reaching its capacity, the switch (1) takes processing time to search for other possible routes over which to send traffic; and (2) devotes resources to handle calls that it ultimately cannot fully process. When the users get blocked, they tend to retry, producing additional stress on the switch and wasting additional switch resources. As the switch becomes over-burdened, it experiences blocking and therefore performance degradation. Eventually, few or no calls are processed as much of the resources are occupied with overhead activities.

EXHIBIT 3-3

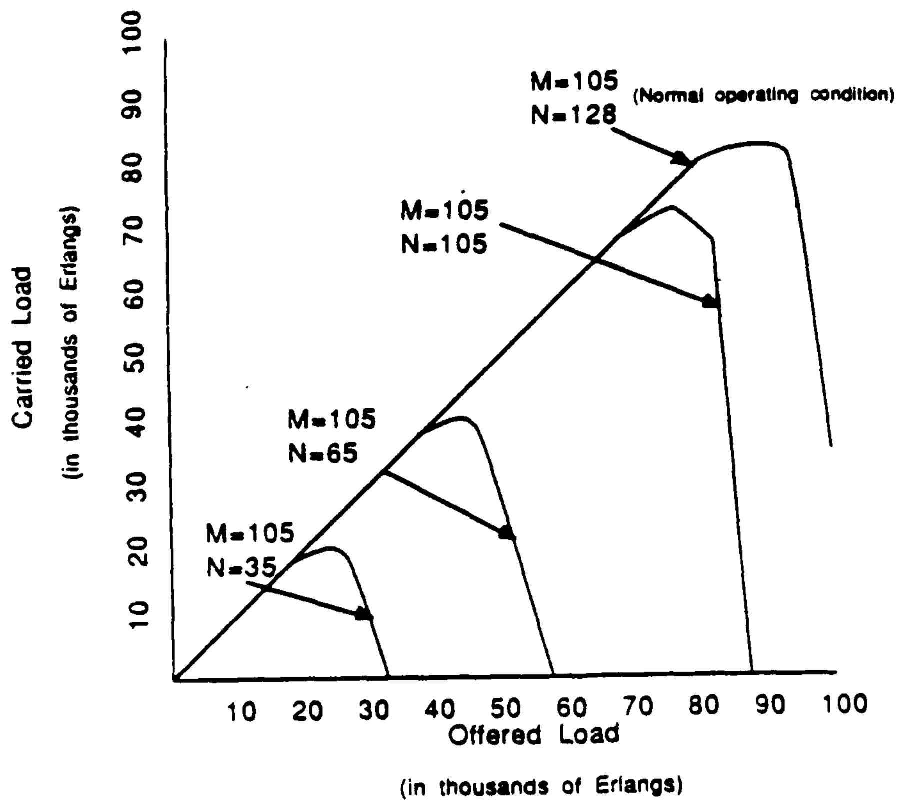
Switch Call Blocking (Reference 6)



Call blocking probability depends on the switch architecture. Among the relevant architecture variants are the number and size of the space and time stages in the switch, the software facilities, and the peripheral devices. As mentioned earlier, the other factor affecting switch blocking is the offered load. A switch designed to be integrated into the toll network will handle 70 percent of its lines during the maximum busy period. In other words, the average line utilization rate is (p = .7). At the local level the average subscriber line may only be used 10 percent of the time (p = .1). When these expected p values increase substantially from their designed goals, blocking can be expected.

Analysts, such as C.Y. Lee and C. Jacobeus, have developed methods for estimating the switch call blocking probabilities. Exhibit 3-4 shows the results obtained by applying the Lee model, as described by Cieslak and Hickson in Reference 7, to the No. 4ESS six stage Time-Space-Space-Space-Space-Time (TSSSST) switch.

EXHIBIT 3-4
Blocking Probability of the AT&T
TSSST 4ESS Digital Switch



M=Input lines
N=Internal switch lines (which decrease following EMP exposure)

The Lee model uses the following two equations to predict switch blocking.

(3-3)
$$P\{B \mid Z=1\} = \{p_2{}^4 + 4p_2{}^3q_2(1-q_1q_3) + 4p_2q_2{}^3[q_3p_1{}^2 + p_3(1-q_1q_3)] + 2p_2{}^2q_2{}^2[(1-q_1q_3)^2 + 2 - q_3(1-p_1{}^2) - q_1(1-p_3{}^2)] + q_2{}^4[1-(1-p_1{}^2) \cdot (1-p_3{}^2)]\}^4$$

where P{B/Z=1} = the blocking given that Z = 1 channel is idle
p = line occupancy or utilization factor
q = 1-p.

(3-4)
$$P_L\{B\} = \left[1 - \left(1 - \frac{M}{N}p\right)^2 (1 - P\{B \mid Z=1\})\right]^N$$

where $P_L\{B\}$ = the Lee total probability that the attempt to set up a connection across the network will be blocked
P{B/Z=1} = the blocking given that Z = 1 channel is idle
M = the number of trunks
N = the number of time slots.

In Exhibit 3-4, the curve where M=128 and N=105 illustrates the 4ESS in its normal operating environment. This curve indicates that the switch can handle up to 100,000 trunks with a p of .9. As various switch components fail and the number of internal time slots decrease, the call processing capabilities of the switch also decrease. This is indicated in the other three curves where N decreases to 105, 65, and 35. Note that when only 35 time slots are operating the switch can only handle 20,000 calls, as compared to the 90,000 calls it can normally handle.

3.2.3 User Service Time Delays

As in the Erlang B formula previously discussed, the OMNCS time delay assessment assumes that the call arrival process obeys a Poisson distribution and that the blocked calls leave the system after a busy signal. Further, the investigation assumes the subscriber who receives the busy signal will in most cases repeat his call after a period of time. This time period equates to the time a user waits before having a call successfully completed. The OMNCS plans to calculate the resultant time delay distribution due to network congestion and determine the expected time delays experienced by users.

The probability that a call experiences congestion (busy signal) and is therefore delayed is given by the Erlang Delay Formula, typically called the Erlang C equation:

$$\text{(3-5)} \quad \text{Prob(delay)} = p(>0) = \frac{NB}{N - A(1 - B)}$$

where N = the number of servers
A = the offered load
B = the blocking probability.

Assuming Poisson arrival rates and negative exponential holding times the Erlang C traffic model expresses delay probabilities. Sometimes average delay is desired, while at other times the probability of the delay exceeding some specified value, given in equation 3-6, is of more interest:

$$(3\text{-}6) \quad p(>t) = p(>0)\ e^{-(N - A)t/tm)}$$

where $p(>0)$ = the probability of delay greater than 0
t_m = the average service time.

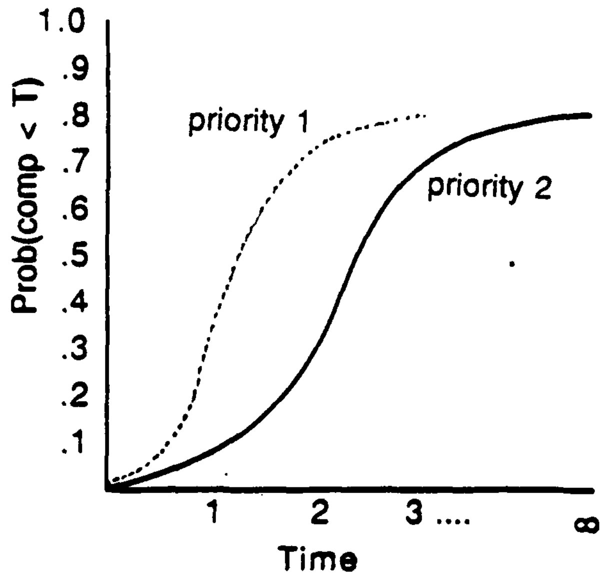
As a form of network optimization (minimization of the user delay), the average call arrival rate parameter, λ , from the expression for average traffic load, $A = \lambda t_m$, may be regulated. That is, if the call arrival rate is too fast, overload and user delays exist which results in a high blocking probability. On the other hand, if the call arrival rate is too slow, the network is not operating at full capacity. This last event also translates into increased user delays because the time before facilities become available to service the user is not at its minimum.

3.2.3.1 Priority and Preemption. Most real time systems are capable of a priority or preemption scheme, though neither is used in the PSN. Under a particular threat, a priority/preemption plan should improve the responsiveness of NSEP telecommunications. Therefore, the OMNCS intends to investigate the roles of both priority and preemption for meeting the NSEP telecommunication needs of the Federal Government.

Priority relates to a user's rights over telecommunications resources. For example, a set of regulations under NSEP conditions could be developed, where each user is designated a particular NSEP telecommunication service level, which is equivalant to a priority. Exhibit 3-5 shows that the service time delays are less for user's with higher priority privileges. The priority 1 user is granted precedence over the priority 2 users in accessing the network. One disadvantage of priority is that if there is an overload of priority 1 users, a situation exists where priority 1 users must wait for other priority 1 users. As shown, the priority 1 user exhibits smaller time delays than the priority 2 user, but with a similar delay probability distribution. In order to get priority, the network must be capable of queuing calls.

EXHIBIT 3-5

Delay Probability Distribution



Preemption, used in the Automated Voice Network (AUTOVON), means that, first, a call is interrupted and terminated. Second, the circuit is appropriated for another user. Priority is the provision of resources before a connection is attempted; preemption is a seizure of resources whether or not those resources are in use.

3.3 INITIAL INVESTIGATION

To meet the objectives of the EMP Mitigation Program, the OMNCS will assess the blocking switch and the server contention on a non-blocking switch both through a full-scale simulation study and by analytical methods to determine network performance characteristics. For the analysis the OMNCS will ask the following fundamental performance questions:

- What is the degree of blocking, that is, what is the probability that a connection request will be blocked? Alternatively, what capacity (N) is needed to achieve a certain upper bound on the probability of blocking?

- If blocked calls are queued for service, what is the average delay? Alternatively, what capacity is needed to achieve a certain average delay?

Future work may focus on the more complex case of server contention on a switch that incurs blocking.

Either the switch or the server contention could be a bottleneck and inhibit call completion. As a first approximation, one can treat the problems separately and size the system based on which component is the bottleneck. Section 3.3 addresses only server contention in the results of this initial analytical study. These results represent an upper bound for network performance in an EMP stressed environment.

Based on previous analyses using the models discussed in section 2.0 and equipment survivability tests, data was obtained that reflect both permanent and partial equipment degradation effects. As a result of these analyses, the number of post-attack surviving trunks was determined and used as input to the initial investigation. Because it is important that the results of these analyses be interpreted in the proper context, two initial conditions are offered. One, the PSN equipment survivability is based on limited test data. Two, the entire network was exposed to one of three uniform stress levels. A complete discussion of the assumptions and initial conditions under which EMP network effects were evaluated is presented in Reference 8.

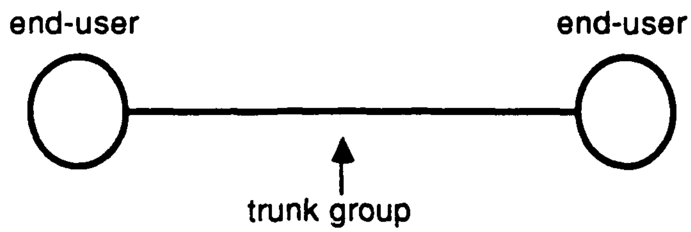
The goal of this initial investigation is to show (1) the effects on network performance following the loss of a specific number of servers and (2) the impact of blocked retries. Exhibit 3-6 illustrates a simplified version of the network; all network resources (servers) are modeled as a trunk group. The Erlang B equation, discussed in section 3.2.1 and shown in equation 3-7, is used to calculate the reduced traffic load necessary to maintain a constant blocking probability between the pre-attack and post-attack networks. This computation yields, for a given quality of service and number of lost servers (trunks), the reduced number of users supported by the network. These results are presented in Exhibits 3-7 and 3-8. Appendix A features further detailed derivations of the Erlang B equation.

$$B = \frac{A^N}{N! \sum_{i=0}^{N} \left(\frac{A^i}{i!} \right)} \qquad (3\text{-}7)$$

where B = Call blocking probability
N = Number of servers (trunks); pre-attack, N = 175k
A = The traffic load on the network

EXHIBIT 3-6

Initial Investigation Network Structure



When servers are lost, the offered load must be decreased if the network is to handle all the traffic. For N servers, Exhibit 3-7 illustrates the variations in carried load (calls completed) as a function of offered load. The horizontal axis represents the number of servers lost due to EMP while the vertical axis specifies the corresponding number of users that must be removed from the network if call blocking is to be avoided. The exhibit is based on the call blocking Erlang B formula and takes into account the effect of retries, i.e. calls that are originally blocked and then reattempted by the call initiator.

Also displayed on the horizontal axis is the EMP field strength at three stress levels of low, medium and high, which correspond to field strengths of 10-30 kV/m, 30-50 kV/m, and 50-70 kV/m, respectively. Using the modeling tools presented in section 2.0, it has been predicted that roughly 49,000 servers are lost at the low level, 73,000 are lost at the medium level, and 123,000 are lost at the high level. These points can be processed with the figure to find out how many users need to be removed from the network at these levels. As indicated there is practically a one to one relationship of servers lost to the number of users which need to be removed. Such type of information can be very valuable for planning NSEP telecommunication responsibilities; given the surviving available telecommunication resources what requirments should be assigned to the various NCS workers.

Exhibit 3-8 illustrates the effect of call blocking for three offered load rates of 25,000, 75,000 and 150,000 simultaneous calls. Note how the call blocking practically changes as a step function, as it migrates from 0.0 to almost 1.0. For example, referring to the offered load rate of 75,000, the network can lose up to 100,000 servers and still remain relatively block free. But as soon as 102,000 servers are lost, the blocking probability at that load rate is roughly unity. With greater resolution the horizontal and vertical lines of the exhibit would actually appear as smooth curves, but because the change in blocking probability is so quick, they appear as step functions in Exhibit 3-8. This instantaneous change in call blocking occurance is due to the spiralling effect of retries. The blocked users reattempt their calls, they cannot be processed by the transmission facility and are therefore likely blocked again. The users attempt the call again and the process repeats itself.

EXHIBIT 3-7

Required Reduction in Offered Load

versus Lost Servers (w/ retries)

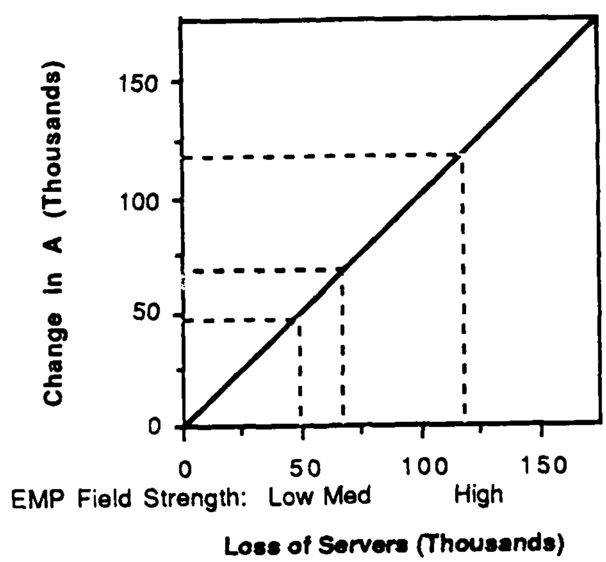
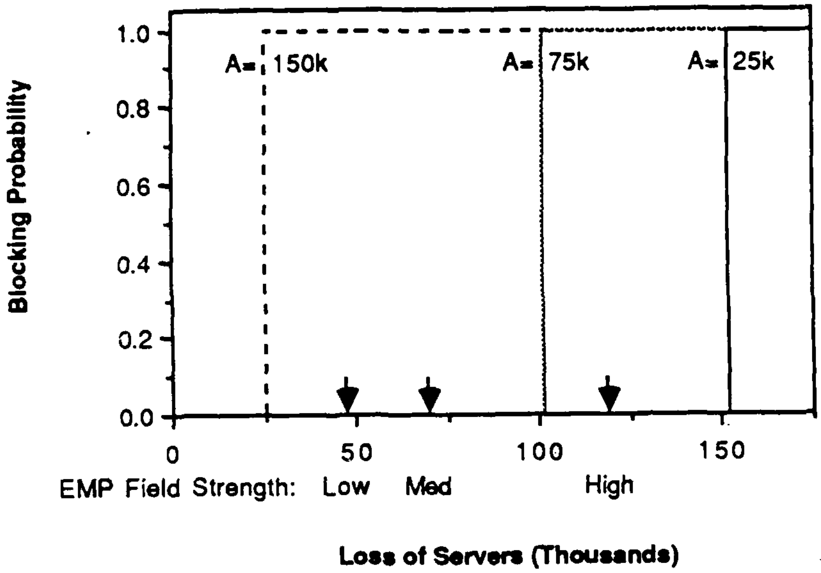


EXHIBIT 3-8

Effects of Servers Lost on Blocking Probability

(w/ retries)



This initial investigation is the first attempt to modeling the decrease in offered load required to maintain a constant blocking probability as trunks are lost due to EMP. Four caveats are offered to ensure that these analyses be interpreted in the proper context:

- The analyses address server contention within non-blocking switches; blocking switches are not incorporated into the network under study

- Equipment survivability is based on the EMP testing of a limited set of equipment types, many critical equipment types such as the 4ESS switch have not been tested and their survivability is estimated. This estimation can lead to significant errors in predicting the number of surviving trunks.

- The actual network is much more complex than described in this first investigation

- The results represent and upper bound; that is, they err on the side of good service.

It is stressed that these preliminary results are better than could be expected, as only trunk blocking is being addressed, and that an actual network would likely support less users following EMP exposure. These results are solely presented to show initial efforts within the OMNCS to assess user traffic demands, and are not presently intended for NSEP planning purposes.

3.4 SUMMARY

EMP exposure may render a switch either temporarily inoperative or permanently disabled. Current modeling capabilities including, BSM, EMPEAK, and NCAM, focus on the effects of disabled equipment on network performance. The Network Dynamic Stability Analysis will be structured to address two sets of issues: first, those associated with the effects of reduced switch functionality; and second, those associated with the effects of increased network traffic in an EMP stressed environment. Both sets of issues contribute to network overload and decreased network efficiency.

The data obtained using the established models and those in development will afford the OMNCS with an ability to test the following propositions related to network stability.

- Reduced processing capability of network facilities, as a result of EMP exposure, could significantly affect network responsiveness.

- Results of switch modeling and simulations may directly reflect network behavior.

- Decreasing offered load or applying alternate routing mechanisms are necessary to maintain efficient network operation during equipment degradation/failures and traffic overloads.

- OMNCS initiatives NETS, CNS, and CSI provide appreciable increases in end-user connectivity and call availability.

The results of these propositions to the observed data will support ongoing efforts to avoid the occurrence of overload by detecting its source and finally reducing its affect.

4.0 EQUIPMENT TESTING

The existing network performance models presented in section 2.0 and the future capabilities described in section 3.0 provide a basis for evaluating the survivability of telecommunications networks against the effects of HEMP. However, the use of these models requires specific information regarding the survivability of the equipment that comprises the networks of interest, including data describing both permanent damage of the equipment and loss of functionality. Some of this information can be extracted from the results of EMP testing programs that have been supported in the past; other data will be collected during future, OMNCS-sponsored testing of telecommunications equipment.

Care must be taken in interpreting the data collected and assessing equipment survivability. Permanent damage and loss of functionality of equipment do not necessarily preclude survivability for all intended uses of the equipment. To determine survivability, the type and extent of the EMP effects must be compared with the requirements for the specific application of interest. The EMP Mitigation Program uses the NCAM modeling capabilities to evaluate the significance of these effects in terms of network connectivity, and selects the connectivity metric (i.e. physical connectivity, logical connectivity, call blocking probability) that is of greatest interest to the initiative being evaluated.

This section discusses general issues related to the effects of EMP on telecommunications equipment, including both permanent damage and the loss of functionality. It also describes the types and formats of the data that are required by the OMNCS for this program. The results of a few test programs are also presented as examples of the data to be collected.

4.1 PHYSICAL SURVIVABILITY

For this program, the OMNCS considers a piece of equipment to be physically survivable if the equipment can perform all essential telecommunications functions following an HEMP event, without the replacement of any piece parts, circuits or subsystems. This definition of survivability permits the intervention of equipment operators to reload software and reset equipment. This definition also permits loss of functionality during and immediately following the HEMP event, provided that the equipment regains operability within a reasonable length of time.

The essential telecommunications functions depend on the type of equipment and its projected role in providing capabilities for NSEP initiatives of interest to the OMNCS. For example, a digital telecommunications facility, like a T1 Cable System, has relatively few essential functions, such as providing a telecommunications channel with an acceptable bit-error rate. On the other hand, a switch for local switching applications may have a variety of essential functions, such as providing dial tones, providing busy tones, making local and toll connections, and maintaining synchronization with the network. However, there may be many operations performed by the equipment under normal conditions that are not essential to NSEP capabilities. These operations may include maintaining billing information, reproducing prerecorded messages, and performing self-diagnostics. While these functions may be fundamental to the economic operation of the equipment, they may not be essential for NSEP capabilities.

The OMNCS gathers information concerning the physical survivability of the equipment from various test programs, including those sponsored by the OMNCS and those sponsored by other government agencies. Such programs typically comprise some combination of equipment testing in simulated EMP environments, and analytical extrapolations and predictions of performance. A summary of the available data is found in Reference 1.

Under the EMP Mitigation Program, the OMNCS analyzes the available data of interest and summarizes it in a format suitable for inclusion in its network models. While the data collected during OMNCS sponsored test programs is readily presented in the appropriate format, other programs exhibit a wide variety of goals, objectives and requirements. The programs do not all use the same description of the EMP threat nor do they all use the same definition of physical survivability.

However, to be of use to the OMNCS, the results of all of the programs must be synthesized into a consistent format. Theoretical test results are presented for a hypothetical system in Exhibit 4-1 to indicate the format required by the Bayesian Survivability Model (BSM), as presented in section 2.0. In this format, the test and analysis results are grouped into three EMP stress level bins: low (10 - 30 kV/m), medium (30 - 50 kV/m) and high (>50 kV/m). For each bin, the data are presented in terms of the number of events and the number of successful events, or events through which the equipment survived. Unfortunately, this is rarely the format of the results of test and analysis programs not sponsored by the OMNCS. Therefore, analytical techniques such as those used in Reference 1 are used to relate the reported results to the stress level bins used by the OMNCS in this program.

Synthesizing the results of disparate assessment programs into a single format is often difficult, and is not accomplished without the introduction of error. The sources of these errors are varied and not easily quantified. For example, most equipment types of interest to the OMNCS are available in a wide variety of models. T1 Carrier systems can employ virtually

EXHIBIT 4-1

Survivability Results for Hypothetical Equipment Illustrating Required Data Format

EMP Stress Level	Total Events	Successful Events
Low	50	50
Medium	40	38
High	35	10

every type of twisted pair cable available in the PSN, including some that are designed specifically for T1 applications. These include both aerial and buried installations, as well as installations combining the two. T1 repeater equipment (both line and office type repeaters) are available in a variety of models and may be installed with various lightning protection schemes or no lightning protection at all. A T1 system may include a channel bank for conversion of the signal to an analog format, if it is to be interfaced with an analog system. The repeater and office equipment also may be installed in a variety of buildings/enclosures, with different grounding, power and lightning protection specifications. Versions of the equipment that are designed specifically to withstand severe electromagnetic environments, possibly including EMP environments may exist.

The equipment variations mentioned here are only an indication of the complexity involved with characterizing a "typical" installation. The existence of these variations indicates the type of difficulty involved with quantifying the effects of EMP on telecommunications equipment. The variety of equipment types, installation practices and standard operating procedures is one of the major reasons that the OMNCS is forced to use a statistical, rather than deterministic methodology. A deterministic model would require a data base containing a detailed description of each installation, including procedures used and equipment installed. Such a data base would also require continual updates to ensure accuracy. The collection of such information would be a monumental task, which would be further complicated because the data would likely be considered proprietary by the operating companies.

Other sources of error in the methodology are related to the EMP environment used for the assessment. For its assessments, the OMNCS uses both an unclassified, 50 kV/m double exponential pulse description (Reference 9) and the classified early-time (E1) portion of DOD-STD-2169 (Reference 10). Any other threat description used in other programs represents a possible source of error. The interaction of the environment with the equipment being assessed is also affected by the assumed polarization of the field, and angles of incidence and orientation, as well as the assumed conductivity of the earth. Each of these parameters affects the magnitude and duration of the currents induced onto conductive elements (i.e., wires, metal enclosures and towers) that comprise the systems under test. Thus, each of these issues represents a possible source of additional error in EMP survivability assessments.

An assessment methodology that incorporates each of these issues in a deterministic manner is inappropriate for the OMNCS for two reasons: the costs involved could be exorbitant and number of years of effort required before benefits could be derived from the program could be excessive. The collective risk approach of the BSM (see section 2.2) addresses these issues statistically, rather than deterministically. As the amount of available test data increases, the ability of the BSM to accurately characterize performance of the entire population of each equipment type increases. It is through this approach that the OMNCS can assess equipment survivability in a cost effective manner.

4.2 LOSS OF FUNCTIONALITY

As a result of some of the initial OMNCS sponsored testing of the 5ESS digital switch (see Reference 11), the OMNCS has identified the need to characterize not only the physical survivability of the telecommunications equipment (particularly the switching systems), but also the transient response of the equipment as well. In response to the simulated EMP as part of the assessment program, the 5ESS experienced some loss of functionality at all field-strength levels. Some of the upset was restored automatically by the system; some of the upset required manual intervention by the operator. As described in section 3.0, this transient upset could have a profound impact on the performance of the network in a post-attack period. For this reason, it is of great importance that loss of functionality be included in the characterization of the equipment performance.

For the purposes of this program, loss of functionality is the loss of some or all essential telecommunications functions that can be recovered without the replacement of any subsystem, box, card or device. Any amount of operator intervention is permitted, as long as no hardware is replaced. This type of system response is also referred to as system upset. Loss of functionality is typical of the EMP response of digital systems, particularly modern, sophisticated systems.

Although the focus of the EMP community traditionally has been permanent damage effects, upset is the subject of increasing amounts of interest and work. As an evolving science, the tools for predicting and characterizing these effects have yet to be completely developed. Standard methods of protecting equipment from EMP-induced upset are also under development. The design of the 5ESS includes software and hardware to detect and correct errors and circuit upsets. However, it was not designed specifically to address EMP-induced errors.

The most simple type of functionality loss experienced by the 5ESS is handled automatically by the switch, with little effect on system operability. This type of upset is interpreted by the system as noise on transmission lines. Digital telecommunication switches are typically equipped with error detection hardware and software to handle such noise. When an unacceptable error rate (caused by the EMP event) is detected, the affected line termination hardware is removed from service, and alternate hardware is automatically used to replace the affected unit. The affected unit is then tested, either automatically or manually, and returned to service, if it is determined that there is no problem with the hardware. Typically, the scenario presented does not affect the ability of the switch to perform its telecommunications functions after the EMP event.

More complicated upset scenarios have been experienced, and are a greater problem for the equipment. One of the first upsets discovered in the 5ESS program was the disabling of major sections of the equipment due to overvoltages on the power supply leads. All of the power supplies for the various racks of equipment have overvoltage sensors that are designed to disconnect power to the rack in the event that the equipment is drawing too much power. During the EMP event, the overvoltage sensors detected voltages in excess of specifications on the power supply lines. In response to the perceived overvoltage, the power was removed from the entire rack of equipment, thereby shutting down major portions of the switch. For safety reasons, the power supplies will not be reactivated until they are manually reset. For the 5ESS, the problem was remedied with relatively minor changes to the sensor circuit design. Such solutions may or may not be as simple for other equipment or sets of equipment. More significantly, such problems may not be discovered in other equipment types until they are tested under an EMP simulator.

During the 5ESS program, some equipment was automatically removed from service so it would not be restored without manual intervention. An example of this type of failure results from the use of distributed processing architectures. A controller is used to coordinate the activities of several line termination units, including the switching between redundant circuits and testing of circuits that exhibit unacceptable error rates. When one of the units encounters unacceptable amounts of errors, it sends a request to the controller. The controller then switches the call processing responsibilities to the redundant circuits, and schedules the faulty equipment for testing. Unfortunately, the controllers have a finite length queue for testing requests. Once the queue is filled, additional requests are ignored. If the request is ignored, only manual intervention can return the equipment to service. In this way, operational circuits can be eliminated from service, reducing call processing capabilities until an operator intervenes.

Maintaining greater amounts of memory to facilitate longer queues for service requests is the logical solution to this problem. This, however, is treating the symptom, and not the problem. The problem is that the error detection and correction software and hardware are designed to handle, in a cost-effective manner, the types of error patterns the switch is expected to experience. To address the problem correctly, the software and hardware should be designed to address EMP-induced upsets.

Another type of error exhibited during the 5ESS program has been described as a software-induced transient upset. For example, the 5ESS maintains a data record for each established call that contains the important information regarding that call. As a result of the EMP event, some of these records were contaminated with erroneous data. The operating software of the switch could, at some time after the EMP event, detect the inconsistency in the data. When the data record is found to be contaminated, the software is designed to drop the call, release the equipment for another call, and clear the call from its memory. Unfortunately, this happened for calls that had been physically unaffected by the EMP event. This was verified by test technicians talking on the lines after the event until the time that the call was aborted by the switch.

These examples indicate the wide range of upsets that may plague a modern, digital system. The types of functionality loss experienced by digital equipment other than the 5ESS may be entirely different. Unfortunately, the understanding of the cause and effects of these problems is in its infancy. Identification of the potential problems is still extremely difficult and defining solutions to the problems is quite expensive. Furthermore, any solution must address not only the performance of the system in an EMP environment, but also the cost-effective operation of that equipment on a daily basis.

To be of use to the OMNCS, the results of tests and analyses regarding transient upset must be synthesized into a standard format, such as indicated in the sample data presented in Exhibit 4-2. At minimum, the data must be reduced to indicate for each event the number of lines (channels) that could support a call. For the initial analyses, it is sufficient to provide this data for switch performance long after the EMP, at a time following the event where the switch has stabilized. As the capabilities of the NCAM modeling tools increase, data will be required as a function of time after the EMP event. These data are required for a variety of field strengths, much like the physical survivability data. Ideally, data would be collected for a variety of loading conditions. As indicated in section 3.0, the performance of a switch may be a strong function of the offered load.

Unfortunately, the range of available offered loads is determined by the test setup and other limitations. For example, the offered load is limited by the number of calls that can be simulated by the call simulator used for the test. The offered load is also limited by the size of the equipment used for the test. For example, the 5ESS as configured for the test program could terminate only 256 lines. However, it contained two administrative modules and two time slot interchange frames, which is the same number found in a switch designed to terminate 100,000 lines. Such a system design precludes placing a sufficiently high offered load on the switch to fully characterize switch performance. Unfortunately, such a system design is often dictated by the test logistics and cost constraints of performing such an assessment.

EXHIBIT 4-2

Example of Transient Upset Data

EMP Stress Level	Total Lines	Operational Lines
Low	1234	1234
Low	1234	1201
Low	1558	1553
Medium	1189	678
.	.	.
.	.	.
.	.	.
High	1245	345

4.3 EXAMPLE TEST RESULTS

To illustrate the type of data and the format required for this program, results for the T1 carrier system and the 5ESS switching system are presented in this section. No analysis or interpretation of the raw data is presented here; the results are drawn directly from Reference 1.

4.3.1 T1 Carrier System Results

The results of simulator testing of the T1 carrier equipment are summarized in Exhibit 4-3. The first set of data presents survivability of line repeaters; the second set of data presents survivability of central office equipment. These data indicate that the T1 carrier facilities are robust to HEMP effects.

EXHIBIT 4-3
Interpolated Buried T1 Carrier Test Results

Line Repeater Results

Stress Level (kV/m)	Sample Size	Failures
10-30	17	0
30-50	6	0
50-70	4	0

Central Office Results

Stress Level (kV/m)	Sample Size	Failures
10-30	8	0
30-50	6	0
50-70	4	0

4.3.2 5ESS Switching System Results

Exhibit 4-4 summarizes the 5ESS switch test results as used in the BSM. The exhibit indicates that the switch did not have a single physical failure at any of the EMP exposures. However, careful interpretation is required in using these results. It must be stressed that the results presented in Exhibit 4-4 are for a 5ESS switch incorporating the hardware modifications identified in the test report. All of these modifications, with the exception of the optical link to the Master Control Center (MCC), will be incorporated in new 5ESS switches. However, some form of upset occurred at all levels of testing: a significant fraction of calls were dropped, call processing capability was reduced during fault recovery, and automatic restoration of all switch resources was not fully completed. Despite these upsets, the hardware failures experienced did not affect call processing capability. The optical link to the MCC will not be a standard offering on future 5ESS switches. Damage to the TTY interface caused by current transients on the Main Control Console cables would not affect call processing ability of the switch, but personnel at remote sites would not be able to control and monitor the switch after an EMP event.

EXHIBIT 4-4

Interpolated 5ESS Switch Physical Test Results

Stress Level (kV/m)	Sample Size	Failures
10-30	23	0
30-50	166	0
50-70	33	0

Following exposure to simulated-HEMP fields, data were collected every five minutes over a half hour period to monitor the automatic recovery of call processing of the 5ESS switch. Immediately following the test pulse, few, if any, calls were processed. Automatic fault recovery improved the call processing capability of the switch over time, but after 20 to 30 minutes, automatic fault recovery stabilized and there was no further improvement of call-processing capability. Using the call-completion data, the call processing capability of the 5ESS switch is estimated as the percentage of calls that were completed during all the tests at the end of the half hour test period. Testing was conducted using the Horizontally Polarized Dipole (HPD) and ALECS simulators.

During the first 2½ minutes following an HPD pulse, the switch did not process active calls, due to logic disruption and automatic recovery action. The test results are summarized in Exhibit 4-5. After 20 minutes, the call completion rate was between 90 and 100 percent in 90 percent of the test events. The 5ESS was pulsed by the HPD a total of 36 times.

EXHIBIT 4-5

Call Processing Recovery of 5ESS Switch Following Exposure to HPD

Percent of HPD Events	Percent of Call Attempts Completed
90	90-100
4	80-90
2	40-50
2	30-40
2	20-30

Testing under the ALECS simulator was conducted at three field levels: 5-20 kV/m (low field level, 13 events), 25-40 kV/m (medium field level, 15 events), and 45-80 kV/m (high field level, 31 events). The results of automatic call recovery measurements of the 5ESS switch when exposed to ALECS are presented for the three field levels in Exhibits 4-6, 4-7 and 4-8.

EXHIBIT 4-6

Call Processing Recovery of 5ESS Switch Following Exposure to Low level ALECS Fields

Percent of ALECS Events	Percent of Call Attempts Completed
70	90-100
15	80-90
7.5	70-80
7.5	20-30

EXHIBIT 4-7

Call Processing Recovery of 5ESS Switch Following Exposure to Medium level ALECS Fields

Percent of ALECS Events	Percent of Call Attempts Completed
22	90-100
15	80-90
9	70-80
9	60-70
9	50-60
9	40-50
9	30-40
9	20-30
9	10-20

EXHIBIT 4-8

Call Processing Recovery of 5ESS Switch
Following Exposure to High level ALECS Fields

Percent of ALECS Events	Percent of Call Attempts Completed
35	90-100
13	80-90
8	70-80
12	50-60
12	40-50
8	30-40
12	20-30

The automatic call recovery of the 5ESS switch reached a steady-state level after 20 minutes, but this level never reached 100 percent. These steady-state levels are summarized in Exhibit 4-9. The data from the HPD test are combined with the data from the medium-level ALECS tests so that all the data is presented in a consistent format. To combine these data, it is necessary to calculate a weighted average. Within the 36 HPD events, 92 percent of the calls were completed; within the 15 medium-level ALECS events, 62 percent of the calls were completed. By combining these two test results (HPD and medium-level ALECS), the average call completion percentage for medium field strengths is calculated to be 83 percent. These results are summarized in Exhibit 4-10.

4.4 FUTURE TESTING EFFORTS

To support this program, the OMNCS intends to continue developing its data base of equipment survivability through the sponsorship of testing programs. Current plans include testing of the Northern Telecom DMS-100/200 line of switching systems in early FY 1988 and testing of the AT&T 4ESS switching system in

EXHIBIT 4-9

Steady-state Call Completion Percentages
for HPD and ALECS Test Results

Pulser	Field Level (kV/m)	# Events	Steady-state Call Completion Percentage
HPD	Medium	36	92
ALECS	Low	13	87
ALECS	Medium	15	62
ALECS	High	31	71

EXHIBIT 4-10

Steady-state Call Completion Percentages for
5ESS Switch Following Automatic Fault Recovery

Stress Level (kV/m)	Steady-state Call Completion Percentage
Low	87
Medium	83
High	71

FY 1988 and 1989. Other testing will be sponsored as funds and equipment availability allow. The OMNCS will also continue its efforts to include any relevant data collected during other government-sponsored EMP testing efforts.

The equipment to be tested will be selected based on cost of testing and the value of additional information to the accuracy of the network simulations. Sensitivity studies performed by the OMNCS have stressed the importance of the 4ESS and analog and digital microwave equipment to the network model results. Future sensitivity studies will focus on the prioritization of equipment types for testing in the future.

5.0 BENEFITS OF THE OMNCS EMP MITIGATION PROGRAM APPROACH

The OMNCS EMP Mitigation Program approach has been described in detail in the preceding sections of this report. This approach includes an assortment of interrelated models used for evaluating the survivability of telecommunication networks and the data required to support these models. This approach provides the OMNCS with a variety of benefits that each directly or indirectly support the mission of the OMNCS as described in Executive Order 12472. This section describes in detail the benefits of the approach and methodology.

5.1 QUANTIFICATION OF THE EFFECTS OF EMP

The development of the NCAM and the collection of the appropriate supporting data provide the OMNCS with a powerful tool for quantifying the effects of EMP on networks of concern. While various sources of error have been identified in the models, the methodology is designed to identify those sources of error and to identify the data that must be collected to decrease the associated errors. As additional data are collected and as additional capabilities are added to the models, the variance in the results of the model will continue to decrease. The methodology and models described include sufficient flexibility to be easily applied to any of the OMNCS initiatives for which EMP survivability is a major concern; the flexibility allows the OMNCS to respond to changes in the needs and requirements of those initiatives in the future. This flexibility is essential for the OMNCS to easily adapt to changes in the structure and content of the PSN, which is the logical product of the advances in technology and the effects of divestiture of AT&T.

5.2 COST-BENEFIT ANALYSES FOR MITIGATION ALTERNATIVES

Once the effects of EMP on the networks of concern to NSEP initiatives are quantified, alternative strategies for mitigating these effects must be evaluated. The models developed for this program provide a unique and powerful technique for quantifying the change in network survivability that would be associated with any proposed mitigation alternative. Such a capability is the only means available to the OMNCS to determine the value of any proposed hardening approach. Whether the proposed change is a modification of the hardware or software for a particular equipment type, the operations or installation procedures for that equipment, or the network management or design, the NCAM can be used to quickly determine the gain in survivability. The survivability gain is then merged with cost estimates for easy comparison of alternative strategies on a cost-benefit basis.

This type of cost-benefit analysis is fundamental to developing an effective mitigation strategy. The value of the mitigation strategy can be measured solely in terms of the extent to which EMP is removed as a hinderance to regional and national telecommunications capabilities, as required in E.O. 12472. This mitigation strategy will eventually be the product of the EMP program. While there are many ways to determine the effect of any mitigation strategy on an individual switch or transmission facility, the modeling tools developed under this program will provide the OMNCS with the only existing means of quantifying the effects on the performance of the entire PSN.

The ability to evaluate network survivability also provides the OMNCS with an effective tool for evaluating alternative approaches for other NSEP initiatives. For example, the NCAM models could be used to characterize the survivability enhancement that could be expected for the PSN if proposed NETS designs were implemented. This capability gives the OMNCS a tool for contrasting proposed alternative designs and for assessing the cost-effectiveness of the program. NETS is used here as an example, but the capability is equally applicable to other OMNCS initiatives, including Commercial Network Survivability (CNS) and Commercial Satcom Interconnectivity (CSI).

5.3 SENSITIVITY STUDIES

The NCAM and the approach presented here provides the OMNCS with the ability to perform theoretical sensitivity studies on any of the input parameters and data. The results of these sensitivity studies may then be used to quantify the effects of limited input data, to provide input for prioritizing equipment for test and analysis programs, and to quantify the test requirements for equipment assessments.

The OMNCS has performed various sensitivity studies (Reference 11) to determine how much error can be attributed to the lack of data for various equipment types, including the 4ESS, D4 channel banks, and microwave transmission facilities. By using the available data for the remainder of the network and assuming various values for the survivability of the equipment of interest, the OMNCS has shown the importance of the 4ESS and microwave transmission facilities to the performance of the AT&T toll network. Results of the sensitivity study for the survivability of the 4ESS are illustrated in Exhibit 5-1.

The sensitivity studies assigned arbitrary survival probabilities to all 4ESS switches in the network and used the best available data for all other assets. The point-pair connectivity of the surviving network was then computed for each of the three EMP stress-level ranges. The point-pair connectivity was calculated for physical connectivity (denoted PHYSICAL in the exhibit) logical connectivity (denoted BASELINE in the exhibit) and for logical connectivity assuming implementation of proposed NETS call routing capabilities (denoted NETS in the

EXHIBIT 5-1

Sensitivity Study Results for the 4ESS Switching System

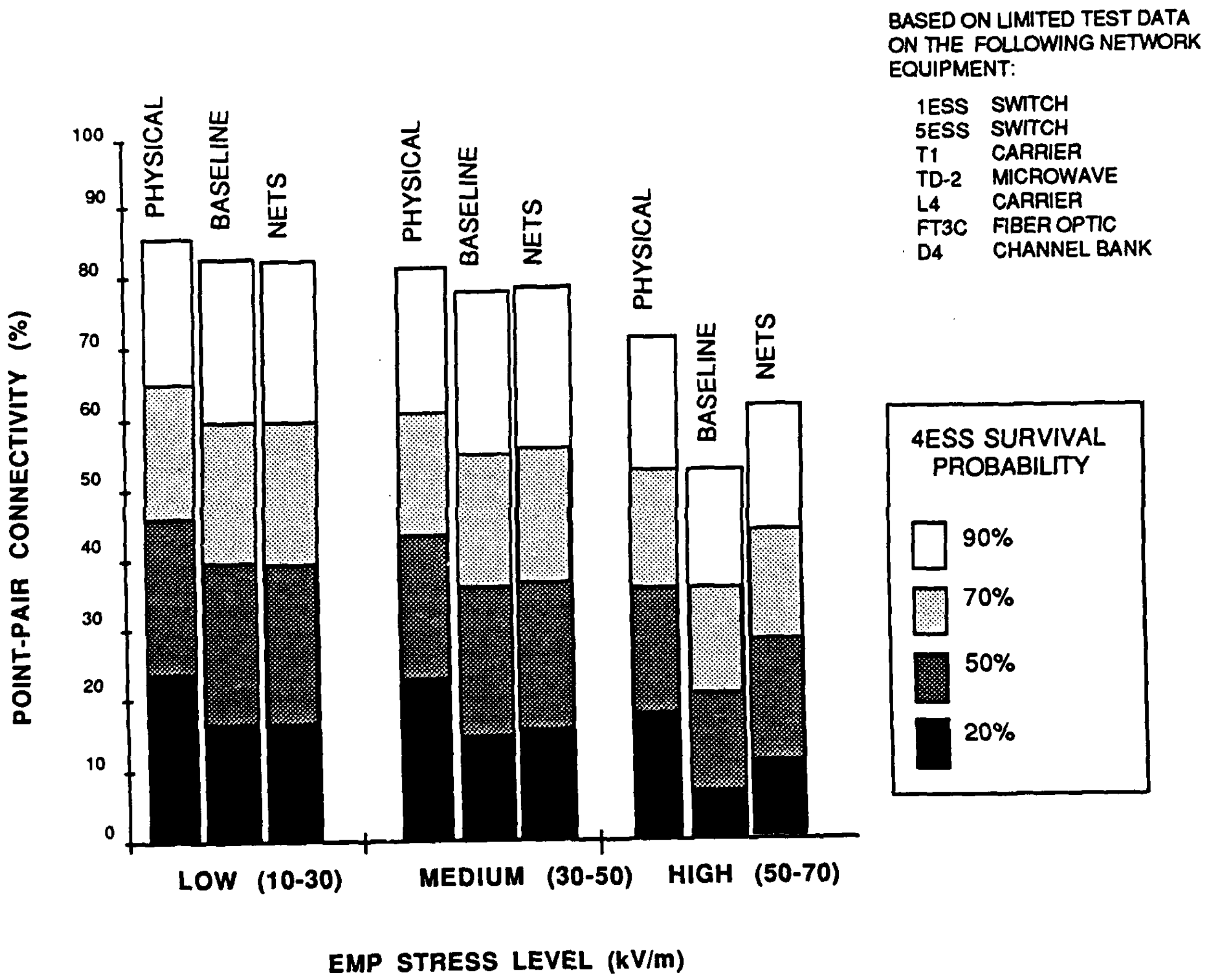


exhibit). The results as summarized in Exhibit 5-1 indicate various significant trends. First, the strong dependence of the results on the assumed survival probability of the 4ESS verifies the extreme dependence of the network on these switches. Second, the difference between the physical and the logical connectivities for high field levels emphasizes the importance of using logical connectivity as the connectivity metric. Third, the significant advantage of NETS call routing capability over baseline capability is demonstrated by the results for high field strengths. The most important result is the tremendous dependence of the network performance on the 4ESS survivability. For this reason, the response of the 4ESS in an EMP environment must be characterized by a combination of test and analysis. Without that information, little confidence can be placed on the predictions of network performance.

The results of sensitivity studies can also be used to help define the requirements for testing programs once an equipment type is selected. Various hypothetical combinations of numbers of test events and test results are used as inputs to the BSM and the NCAM. For each set of hypothetical test results, the mean and variance of the network survivability are computed. These results are then analyzed to determine the minimum number of test events required to support the desired confidence in the network survivability results.

5.4 TEST PROGRAM BENEFITS

The OMNCS benefits from the test programs it sponsors under the EMP mitigation program in several ways. The most direct benefit, enhanced data base for use in the network model, has already been discussed. However, the OMNCS also benefits in other ways. As a result of the testing of the 5ESS, various circuit modifications were identified to enhance the survivability of the switch. In this case, the modifications were so attractive that AT&T has decided to implement them on all 5ESS models produced, at no cost to the Government. As a result, the survivability of 5ESS switches and the network as a whole have been enhanced. Modifications have also been identified for other systems tested (e.g., FT3C Fiber Optic System, D4 Channel Bank). Although these modifications have not been implemented in general, the results of the test program have identified both areas of concern for the OMNCS regarding that equipment as well as options to be considered as part of potential mitigation strategies. Using the information on the effect on survivability at the equipment level, the OMNCS can estimate the effect of the modification on the survivability of the network.

The results of test programs are also helping the OMNCS to develop the understanding of the transient upset effects of EMP. Based on the results of the 5ESS assessment, the OMNCS is better prepared to address the issues of dynamic switch performance in an EMP environment for future testing programs. Furthermore, the OMNCS is using the understanding gained from testing of the 5ESS to develop techniques for characterizing the effects of transient upset on the performance of telecommunication networks.

As a result of EMP assessment programs, the OMNCS is also developing a data base of lessons learned concerning the design, installation, and operation of telecommunications equipment. As the data base is expanded, the OMNCS will be able to look for trends in standard procedures that lead to greater or lesser survivability against the effects of EMP. Identifying the "good" practices (design, installation, or operation), and convincing telecommunications companies to implement them, could be a major portion of the most cost effective mitigation strategies.

6.0 RECOMMENDATIONS

Based on the positive results obtained to date, it is recommended that the OMNCS continue with the approach recommended in this report for the EMP Mitigation Program. This approach has produced promising initial results that will be greatly enhanced with the addition of more data and greater modeling capabilities, as indicated throughout this report. In addition, the following specific items are recommended.

- <u>The OMNCS should continue to use the sensitivity studies for guidance for prioritization of testing efforts</u>. Continued testing of telecommunications equipment will reduce the major sources of variability in the simulation results. The sensitivity study results should also be used to define test requirements for supporting network level simulations. In this way, the available funding for testing can be used so as to ensure the maximum confidence in simulation results. These test programs not only enhance the existing data base to support NCAM, but they also provide insight into telecommunications practices and equipment design.

- <u>The current capabilities of NCAM to predict the EMP field strengths at each location of interest to the OMNCS should be enhanced to more accurately reflect the current understanding of the phenomenology of EMP generation.</u> The predictive capability of the current model can be enhanced without significantly degrading the performance (speed) of NCAM.

- The current capabilities of NCAM should also be enhanced to include dynamic stability analysis to address the effects of user traffic in an NSEP environment. Since the current model capabilities address only static performance, the results may be overly optimistic. Availability requires not only physical and logical connectivity, but also sufficient resources to support the connection. If the network is overloaded, users get blocked, and they continue to reattempt their calls. This has a spiraling effect and eventually the network may not serve any users. The addition of dynamic stability issues will increase the realism of the network assessment capabilities, and may also indicate new areas of concern to the OMNCS, particularly with regard to network management.

- The OMNCS should continue to support EMP testing programs on critical PSN equipment types. Present plans call for testing of the DMS-100 and 4ESS digital switches. Information on the EMP effects on these switches should enhance the understanding of the effects of EMP on digital switching systems. By increasing the amount of test data available to describe the performance of digital switches in an EMP environment, the confidence in the results of NCAM modeling will be greatly enhanced. The results of the previous sensitivity show that data on the 4ESS is fundamental to NCAM predictions of network performance.

- The OMNCS should sponsor a test of modern microwave transmission equipment. Sensitivity studies have indicated a profound dependence of network performance on the survivability of microwave equipment. The only relevant data currently available were collected from equipment based on vacuum tube technology; solid-state equipment may be less survivable against the effects of EMP.

- The OMNCS should begin to formulate a comprehensive mitigation strategy. Once data on the 4ESS, the DMS-100, and microwave equipment have been collected and integrated into the OMNCS data base, sufficient accuracy in model results will have been attained to support the development of mitigation alternatives. Each of the mitigation alternatives must be evaluated to determine the difficulty in implementation, the added network level survivability, the cost of implementation and the means of ensuring implementation. Based on these tradeoffs, the OMNCS should identify a comprehensive mitigation strategy that combines aspects of all of the most attractive alternatives.

As a consequence of all of the work already accomplished and the enhancements identified above, the OMNCS will be able to identify and evaluate alternative mitigation strategies in support of NSEP initiatives. The OMNCS should use the data and other results from the testing programs to develop alternative strategies, including combinations of modifications of equipment design, installation procedures, equipment operations, and network design/management. The NCAM results should be used to quantify potential survivability gains if the strategies are implemented. Those strategies that appear to be practical and economically feasible should be identified. Of those identified, the most promising should be refined and optimized to work together to make the most positive impact on survivability. In this manner, the OMNCS can implement a comprehensive, cost-effective mitigation program to enhance the survivability of regional and national telecommunications capabilities of interest to NSEP initiatives.

APPENDIX A

This appendix provides additional insight into the utility of the Erlang B equation, which is used to predict the blocking probability of a transmission facility. A proof is presented to indicate how many users need to be removed from the transmission facility, when the number of transmission facility servers decreases, in order to maintain the same call blocking probability. This is equivalent to stating that the remaining users have the same quality of service (i.e. call blocking probability) following the loss of a number of servers; and to attain the same service, a number of other users must be removed.

The proof starts with the Erlang B equation.

A-1

$$B = \frac{A^N}{N! \sum_{i=0}^{N} \frac{A^i}{i!}}$$

$A = \lambda \cdot t_m$

λ= Call arrival rate

t_m= Average call holding time

N= Number of servers

B= Call blocking probability

Following an EMP attack the system parameters change. The prime notation is used to identify post-attack parameters.

A-2

$$B' = \frac{A'^{N'}}{N'! \sum_{i=0}^{N'} \frac{A'^i}{i!}}$$

Use the following abbreviation for the summation terms for both the pre- and post-attack conditions.

A-3 $$\Sigma = \sum_{i=0}^{N} \frac{A^{i}}{i!}$$

Delta functions are used to state the differences between pre- and post-attack, blocking probabilities, offered load, and the number of servers.

A-4 $$\delta B = B - B'$$

A-5 $$\delta A = A - A'$$

A-6 $$\delta N = N - N'$$

By algebraic manipulation and the introduction of logarithms, the change in call blocking probability is defined as follows.

A-7 $$\delta \mathrm{Ln}B = \mathrm{Ln}\left(\frac{A'^{N'}}{A^{N}}\right) + \mathrm{Ln}\,\frac{N!}{N'!} + \mathrm{Ln}\,\frac{\Sigma}{\Sigma'}$$

Each of the three terms of Equation A-7 are now solved for individually.

A-8 $$\mathrm{Ln}\left(\frac{A'^{N'}}{A^{N}}\right) = \mathrm{Ln}\left(\frac{A'}{A}\right)^{N} - \delta N \mathrm{Ln}A'$$

Where the first term of A-8 approximately equals for small changes in A

A-9 $$\mathrm{Ln}\left(\frac{A'}{A}\right)^{N} \longrightarrow -N\,\frac{1}{A}\,\delta A$$

The first term of A-7 is then

A-10 $$\mathrm{Ln}\left(\frac{A'^{N'}}{A^{N}}\right) = -N\,\frac{\delta A}{A} - \delta N \mathrm{Ln}A'$$

N! requires significant computer resources, therefore for the second term, the Stirlings approximation is used.

A-11 $$N! = \left(\frac{N}{e}\right)^{N} \sqrt{2 \Pi N}$$

The second term then can be expressed as

A-12 $$\mathrm{Ln}N! = N\mathrm{Ln}N - N + 1/2\mathrm{Ln}\,(N\, 2\,\Pi)$$

A-13 $$\mathrm{Ln}\frac{N!}{N'!} = (N + 1/2)\,\mathrm{Ln}\frac{N}{N'} + \delta N \mathrm{Ln}\frac{N'}{e}$$

The third term is solved by taking a Taylor Expansion.

A-14 $$\frac{\Sigma}{\Sigma'} = \frac{e^{A}}{e^{A'}} \left[\frac{1 - \sum_{i=N+1}^{\infty} \frac{A^{i}}{i!} \Big/ e^{A}}{1 - \sum_{i=N+1}^{\infty} \frac{A'^{i}}{i!} \Big/ e^{A'}} \right]$$

Terms in the denominator and numerator factor out for large N, leaving:

A-15 $$\mathrm{Ln}\frac{\Sigma}{\Sigma'} = \delta A$$

By combining terms, the following expression provides the change in call blocking for changes in servers and offered load.

A-16 $$\delta \mathrm{Ln}B = \delta A - N\frac{\delta A}{A} + N\mathrm{Ln}\frac{N}{N'} + \delta N \mathrm{Ln}\frac{N'}{A'e}$$

A-16 can also be specified in terms of the line utilization factor variable p.

A-17 $$\delta \mathrm{Ln}B = \delta A\left(1 - \frac{1}{p}\right) + N\mathrm{Ln}\frac{N}{N'} - \delta N \mathrm{Ln}p'e$$

Equations A-16 and A-17 are transcendental. By keeping the change in call blocking zero, the equations can specify how many users need to be dropped from the network when a certain number of servers are lost.

The first-cut analysis presented in section 3.0 used the full Erlang B Equation. However, this proof has been presented to provide additional insight to the Erlang B equation, and to illustrate the function of offered load versus the number of servers for a constant blocking probability.

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